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ORIGINAL ARTICLE

Application of Adomian decomposition method for micropolar flow in a porous channel

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Abstract In this study the injective micropolar flow in a porous channel is investigated. The flow is driven by suction or injection on the channel walls, and the micropolar model is used to describe the working fluid. This problem is mapped into the system of nonlinear coupled differential equations by using Berman's similarity transformation. These are solved for large mass transfer via Adomian decomposition method (ADM). Also the numerical method is used for the validity of this analytical method and excellent agreement is observed between the solutions obtained from ADM and numerical results. Trusting this validity, effects of some other parameters are discussed. It can be seen that increasing in the value of N_1 have different results in comparison with N_2.

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1. Introduction

Eringen [1] was the first pioneer of formulating the theory of micropolar fluids. His theory introduces new material parameters, an additional independent vector field – the microrotation – and new constitutive equations which must be solved simultaneously with the usual equations for Newtonian fluid flow. The desire to model the non-Newtonian flow of fluids containing rotating microconstituents motivated the development of the theory, but subsequent studies have successfully applied the model to a wide range of applications including

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blood flow, porous media, lubricants, turbulent shear flows, and flow in capillaries and micro channels. Lukaszewicz prepared last theories and more recent literature [2]. Also in recent years some researchers investigated on micropolar fluids and their phenomenon [3–6].

Self-similar analysis of boundary layer flow of a micropolar fluid in a porous channel, where the flow is driven by uniform mass transfer through the channel walls is implemented. The corresponding Newtonian fluid model was first studied by Berman [7], who described an exact solution of the Navier-Stokes equations by assuming a self-similar solution and reducing the governing partial differential equations to a nonlinear ordinary differential equation of fourth order. The solution is of potential value in understanding more realistic flows in channels and pipes, and study of Berman's exact solution and generalizations of it have attracted numerous studies subsequently, i.e. Yuan [8], Robinson [9], Zaturska et al. [10], and Desseaux [11].

With a view to understanding how the micropolar theory may be used to model realistic non-Newtonian flow applications, micropolar extensions have been considered for this and other problems by some researchers [12,13]. In the absence of extensive experimental data for micropolar fluids, the aim of this paper is to determine how the material constants of the micropolar fluid affect on the flow for large mass transfer through the channel walls. Most of engineering problems, especially some heat transfer equations are nonlinear, therefore some of them are solved using numerical solution and some are solved using the different analytic method. One of the semi-exact methods which does not need linearization or discretization is Adomian decomposition method and several modification has improved its ability [14,15]. An advantage of this method is that, it can provide analytical approximation or an approximated solution to a rather wide class of nonlinear (and stochastic) equations without linearization, perturbation, closure approximation, or discretization methods. Unlike the common methods, i.e., weak nonlinearity and small perturbation which change the physics of the problem due to simplification, Adomian decomposition method (ADM) gives the approximated solution of the problem without any simplification. Thus, its results are more realistic. ADM abilities have attracted many authors to use this method for solving fluid dynamic problems. Recently, several papers have been published about numerical and analytical methods [16–55].

The main intend of this study is to apply Adomian decomposition method to find the approximate solutions of nonlinear differential equations governing micropolar flow in a porous channel with high mass transfer. The fourth order Runge-Kutta method has been used and considered as the numerical solution for validity of this method.

2. Mathematical formulation

We consider the steady laminar flow of a micropolar fluid along a two-dimensional channel with porous walls through which fluid is uniformly injected or removed with speed v_0 as shown in Figure 1. Using Cartesian coordinates, the channel walls are parallel to the x-axis and located at $y = \pm h$ where $2h$ is the channel width. The relevant equations governing the flow are:

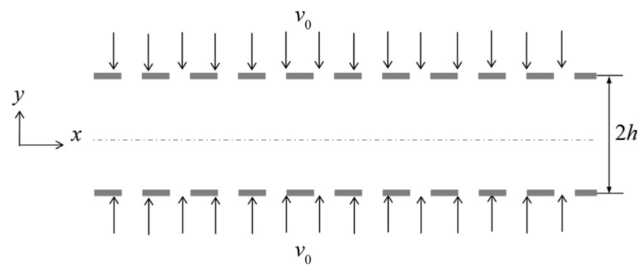

Figure 1 Geometry of problem.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P}{\partial x} + (\mu+\kappa)\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \kappa\frac{\partial N}{\partial y}, \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial P}{\partial y} + (\mu+\kappa)\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \kappa\frac{\partial N}{\partial x}, \tag{3}$$

$$\rho\left(u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y}\right) = -\frac{\kappa}{j}\left(2N + \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right) + \left(\frac{\mu_s}{j}\right)\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right), \tag{4}$$

where u and v are the velocity components along the x- and y-axis respectively, ρ is the fluid density, μ is the dynamic viscosity, N is the angular or micro rotation velocity, P is the fluid pressure, j is the micro-inertia density, k is a material parameter and $\nu_s = (\mu + \frac{k}{2})j$ is the micro rotation viscosity.

The appropriate boundary conditions are:

$$y = -h:\ v = u = 0,\ N = -s\frac{\partial u}{\partial y}$$
$$y = +h:\ v = 0,\ u = \frac{v_0 x}{h},\ N = \frac{v_0 x}{h^2}. \tag{5}$$

where s is a boundary parameter and indicates the degree to which the microelements are free to rotate near the channel walls. The case $s = 0$ represents concentrated particle flows in which microelements close to the wall are unable to rotate. Other interesting particular cases that have been considered in the literature include $s = 0.5$ which represents weak concentrations and the vanishing of the antisymmetric part of the stress tensor and $s = 1$ which represents turbulent flow. We introduce the following dimensionless variables:

$$\eta = \frac{y}{h}, \ \ \psi = -v_0 x f(\eta), \ \ N = \frac{v_0 x}{h^2} g(\eta), \tag{6}$$

The stream function is defined in the usual way:

$$u = \frac{\partial \psi}{\partial y}, \ \ v = -\frac{\partial \psi}{\partial x} \tag{7}$$

Eqs. (1)–(7) reduce to the coupled system of nonlinear differential equations:

$$(1 + N_1) f^{\mathrm{IV}} - N_1 g - Re\,(f f''' - f' f'') = 0, \tag{8}$$

$$N_2 g'' + N_1 (f'' - 2g) - N_3 Re\,(f g' - f' g) = 0, \tag{9}$$

subject to the boundary conditions:

$$\begin{aligned} &\eta = -1 : f = f' = g = 0, \\ &\eta = +1 : f = 0, f' = -1, \ g = 1 \end{aligned} \tag{10}$$

The parameters of primary interest are the buoyancy ratio N, the Reynolds number Re where for suction $Re > 0$ and for injection $Re < 0$ given by:

$$N_1 = \frac{\kappa}{\mu}, \quad N_2 = \frac{\nu_s}{\mu h^2}, \quad N_3 = \frac{j}{h^2}, \quad Re = \frac{v_0}{\upsilon} h, \tag{11}$$

where N_1 is the coupling parameter and N_2 is the spin-gradient viscosity parameter.

3. Fundamentals of ADM

Consider equation $Fu(t) = g(t)$, where F represents a general nonlinear ordinary or partial differential operator including both linear and nonlinear terms. The linear terms are decomposed into $L+R$, where L is easily invertible (usually the highest order derivative) and R is the remained of the linear operator. Thus, the equation can be written as:

$$L\,u + Nu + R\,u = g \tag{12}$$

where Nu indicates the nonlinear terms. By solving this equation for Lu, since L is invertible, we can write:

$$L^{-1} L\,u = L^{-1} g - L^{-1} R\,u - L^{-1} Nu \tag{13}$$

If L is a second-order operator, L^{-1} is a twofold indefinite integral. By solving Eq. (13), we have:

$$u = A + B\,t + L^{-1} g - L^{-1} R\,u - L^{-1} Nu \tag{14}$$

where A and B are constants of integration and can be found from the boundary or initial conditions. Adomian method assumes the solution u can be expanded into infinite series as:

$$u = \sum_{n=0}^{\infty} u_n \tag{15}$$

Also, the nonlinear term Nu will be written as:

$$Nu = \sum_{n=0}^{\infty} A_n \tag{16}$$

where A_n are the special Adomian polynomials. By specified A_n, next component of u can be determined:

$$u_{n+1} = L^{-1} \sum_{n=0}^{n} A_n \tag{17}$$

Finally, after some iteration and getting sufficient accuracy, the solution can be expressed by Eq. (14).

In Eq. (17), the Adomian polynomials can be generated by several means. Here we used the following recursive formulation:

$$A_n = \frac{1}{n!}\left[\frac{d^n}{d\lambda^n}\left[N\left(\sum_{i=0}^{n} \lambda^i u_i\right)\right]\right]_{\lambda=0}, \quad n = 0, 1, 2, 3, \ldots \tag{18}$$

Since the method does not resort to linearization or assumption of weak nonlinearity, the solution generated is in general more realistic than those achieved by simplifying the model of the physical problem.

4. Solution with ADM

According to, Eqs. (12), (8) and (9) must be written as following:

$$\begin{aligned} &L_1 f = \frac{1}{1 + N_1} N_1 g Re\,(f' f''' - f' f''), \\ &L_2 g = \frac{1}{N_2} N_1 (-f'' + 2g) + N_3 Re\,(f g' - f' g), \end{aligned} \tag{19}$$

where the differential operator L_1, L_2, L_3 and L_4 are given by $L_1 = (d^4/d\eta^4)$, $L_2 = (d^2/d\eta^2)$ respectively. Assume the inverse of the operator L_i $(i = 1, 2)$ exists and it can be integrated from 0 to η, i.e.

$$\begin{aligned} &L_1{}^{-1} = \int_0^{\eta}\int_0^{\eta}\int_0^{\eta}\int_0^{\eta} (\bullet)\, d\eta\, d\eta\, d\eta\, d\eta, \\ &L_2{}^{-1} = \int_0^{\eta}\int_0^{\eta} (\bullet)\, d\eta\, d\eta. \end{aligned} \tag{20}$$

Operating with $L_i{}^{-1}$ on Eq. (19) and after exerting boundary condition on it, we have:

$$\begin{aligned} &f(\eta) = f(0) + f'(0)\,\eta + f''(0)\,\frac{\eta^2}{2} + f'''(0)\,\frac{\eta^3}{6} + L^{-1}(N_1 u), \\ &g(\eta) = g(0) + g'\,(0)\,\eta + L^{-1}(N_2 u), \end{aligned} \tag{21}$$

Where $N_i u$ are introduced as:

$$N_1 u = \frac{1}{1 + N_1} N_1 g Re\,(f' f''' - f' f''),$$

$$N_2 u = \frac{1}{N_2} N_1(-f'' + 2g) + N_3 Re\,(fg' - f'g), \tag{22}$$

ADM introduced the following expression:

$$\begin{aligned} f(\eta) &= \sum_{m=0}^{\infty} f_m(\eta), \\ f(\eta) &= \sum_{m=0}^{\infty} f_m = f_0 + L^{-1}(N_1 u), \\ g(\eta) &= \sum_{m=0}^{\infty} g_m(\eta), \\ g(\eta) &= \sum_{m=0}^{\infty} g_m = g_0 + L^{-1}(N_2 u) \end{aligned} \tag{23}$$

To determine the components of $f_m(\eta)$, $g_m(\eta)$ the $f_0(\eta)$, $g_0(\eta)$ are defined by applying the boundary condition of Eq. (13):

$$\begin{aligned} f_0(\eta) &= a_1 \frac{\eta^6}{6} + a_2 \frac{\eta^2}{2} + a_3\eta + a_4, \\ g_0(\eta) &= a_5\eta + a_6, \end{aligned} \tag{24}$$

$$\begin{aligned} f_1(\eta) &= \frac{Re}{1+N_1}\begin{pmatrix} -\frac{a_1}{2520}\eta^7 - \frac{a_1 a_2}{360}\eta^6 \\ -\frac{a_2^2}{120}\eta^5 \\ -\frac{(105\, a_2 a_3 - 105 a_1 a_4)}{2520}\eta^4 \end{pmatrix}, \\ g_1(\eta) &= \frac{1}{b}\left(-N_3 Re\, a_1 a_5 \eta^5 - \begin{pmatrix} 5N_3 Re\, a_1 a_6 \\ +5N_3 a_2 a_5 \end{pmatrix}\eta^4 \right. \\ &\quad - \frac{1}{120}\begin{pmatrix} -40N_1 a_5 \\ +20N_1 a_1 \\ +20N_3 Re\, a_2 a_6 \end{pmatrix}\eta^3 \\ &\quad \left. - \frac{1}{120}\begin{pmatrix} 60N_3 Re\, a_3 a_6 \\ +60\, N_1 a_2 - 120 N_1 a_6 \\ -60 N_3 Re\, a_5\, a_4 \end{pmatrix}\eta^2 \right). \end{aligned} \tag{25}$$

$f_m(\eta)$, $g_m(\eta)$ for $m \geq 2$ be determined in similar way from Eq. (23). Then using $f(\eta) = \sum_{m=0}^{\infty} f_m(\eta)$, $g(\eta) = \sum_{m=0}^{\infty} g_m(\eta)$ lead to following equations:

$$\begin{aligned} f(\eta) &= \sum_{m=0}^{\infty} f_m(\eta) = a_1 \frac{\eta^6}{6} + a_2 \frac{\eta^2}{2} + a_3\eta \\ &\quad + a_4 \frac{Re}{1+N_1}\left(-\frac{a_1}{2520}\eta^7 - \frac{a_1 a_2}{360}\eta^6\right) + \ldots, \\ g(\eta) &= \sum_{m=0}^{\infty} g_m(\eta) = a_5\eta + a_6 - \frac{N_3 Re\, a_1 a_5}{b}\eta^5 \\ &\quad - (5N_3 Re\, a_1 a_6 + 5N_3 a_2 a_5)\frac{\eta^4}{b} + \ldots. \end{aligned} \tag{26}$$

According to Eq. (26), the accuracy of ADM solution increases by increasing the number of solution terms (m). For the complete solution of Eq. (26), $a_i (i = 1, 2)$ should be determined, with boundary conditions.

5. Results and discussion

The objective of the present study was to apply Adomian decomposition method to obtain an explicit analytic solution of micropolar flow in a porous channel (Figure 1). The results were well matched with the results carried out by numerical solution (Rung-Kutta) as shown in Tables 1 and 2 and Figures 2 and 3. Also Figure 2 shows that maximum error occurs near the middle of two plates.

This accuracy gives us high confidence in validity of this problem and reveals an excellent agreement of engineering accuracy. This investigation is completed by depicting the effects of some important parameters to evaluate how these parameters influence this fluid.

Figure 4 shows the effect of N_1 on the rotation profile. As N_1 increases, rotation profile decreases. Also it can be seen that minimum point of this profile shifts to upper plate by

Table 1 Comparison between the numerical results and ADM solution for $f(\eta)$ and $g(\eta)$ when $Re = 0.4$, $N_1 = N_2 = N_3 = 0.8$.

η	Error	
	$f(\eta)$	$g(\eta)$
0	0	0
0.1	3.71E-06	9.41E-05
0.2	6.95E-06	0.00019
0.3	9.29E-06	0.000288
0.4	1.03E-05	0.000389
0.5	9.83E-06	0.000489
0.6	7.86E-06	0.000579
0.7	4.93E-06	0.000633
0.8	2.03E-06	0.00061
0.9	2.83E-07	0.000435
1	0	0

Table 2 Comparison between the numerical results and ADM solution for $f(\eta)$ and $g(\eta)$ when $Re = 0.5$, $N_1 = N_2 = N_3 = 0.5$.

η	Error	
	$f(\eta)$	$g(\eta)$
0	0	0
0.1	5.24E-06	5.45E-05
0.2	1.01E-05	0.00011
0.3	1.44E-05	0.000169
0.4	1.75E-05	0.000231
0.5	1.92E-05	0.000293
0.6	1.89E-05	0.000349
0.7	1.62E-05	0.000381
0.8	1.09E-05	0.000363
0.9	4.07E-06	0.000252
1	0	0

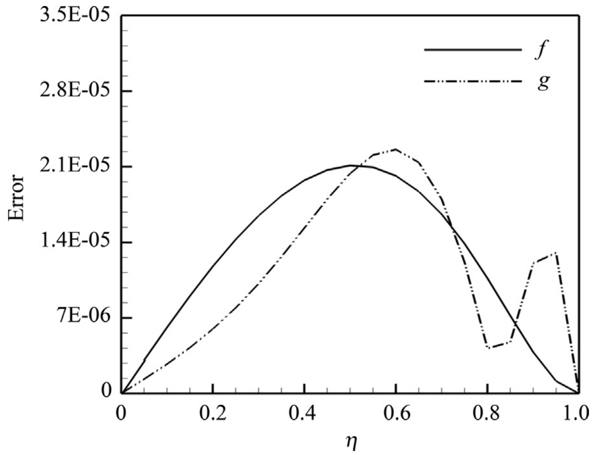

Figure 2 Error for $f(\eta)$ and $g(\eta)$ versus η when $N_1 = N_2 = N_3 = 0.2$ and $Re = 0.5$.

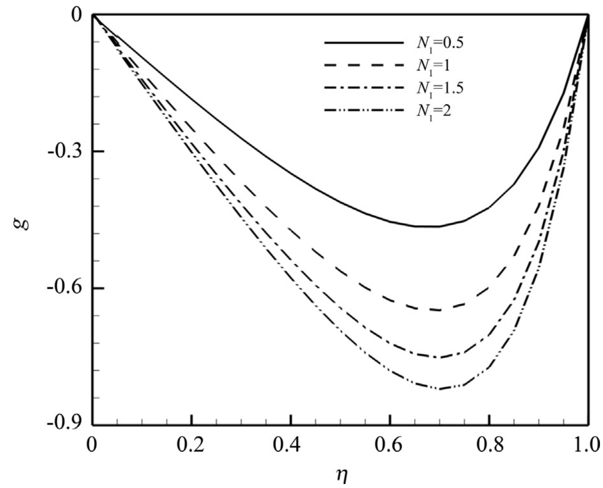

Figure 4 Effect of N_1 on the g when $N_2 = N_3 = 0.2$ and $Re = 5$.

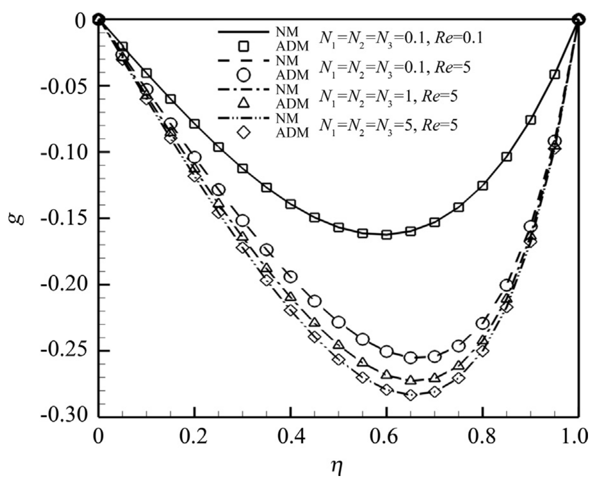

Figure 3 Comparison between numerical and ADM solution results.

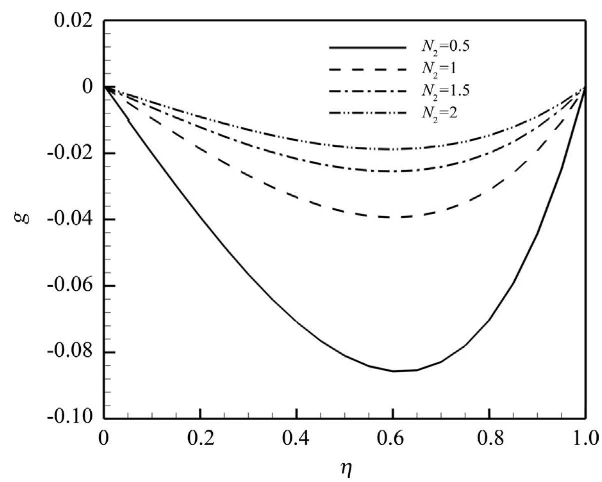

Figure 5 Effect of N_2 on the g when $N_2 = N_1 = 0.2$ and $Re = 5$.

increasing N_1. Figure 5 shows that the effect of N_2 on the g profile. Effect of this parameter on velosity profile is opposite of that of N_1. Effect of N_2 on the rotation profile is shown in Figure 6. Inceasing N_3 leads to decrease in g profile which is similar to N_1 effect.

Figure 7 shows the effects of Reynolds number on rotation profile of fluid. It is interesting to note that rotation profile decreases with an increase in the Reynolds number Re, up to approximately $\eta = 0.6$ and thereafter increases with increasing Re. In a general manner, there is an increment in rotation profile from suction to injection. Also from these figures we observe that with an increase in the value of the Reynolds number the point at which minimum rotation occurs does not move away from the origin of the channel.

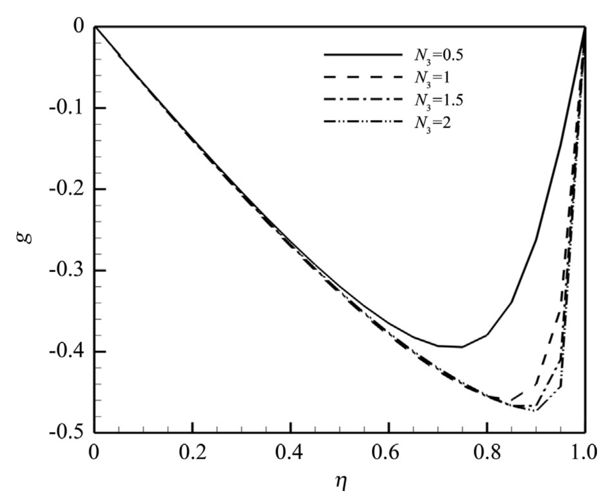

Figure 6 Effect of N_3 on the g when $N_1 = N_3 = 0.2$ and $Re = 5$.

6. Conclusion

In this paper, micropolar flow in a porous channel is solved via a sort of analytical method, Adomian decomposition method, Also this problem is solved by a numerical method (the Runge-Kutta method of order 4). Adomian decomposition method a powerful approach for solving nonlinear differential equation such as this problem, also it can be

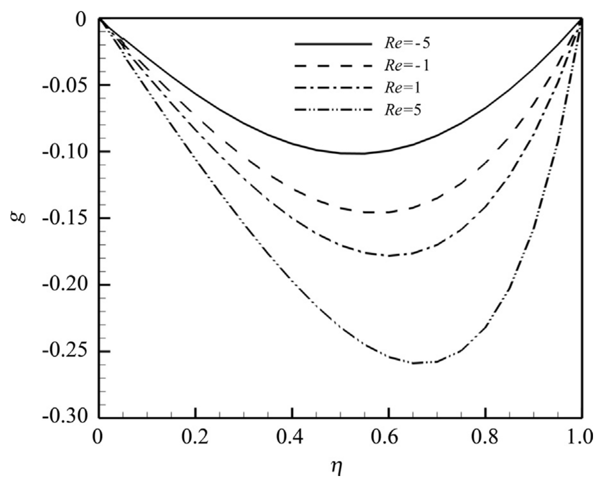

Figure 7 Effect of Re on the g when $N_1 = N_3 = 0.2$ and $N_2 = 0.2$.

observed that there is a good agreement between the present and numerical result. It can be seen that increases in the value of N_1 have different results in comparison with N_2 increasing. rotation profile increases with increase of N_1 and decreases with increase of N_2. There is an increment in rotation profile from suction to injection.

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